Using Direct-Push Tools to Map Hydrostratigraphy and Predict MTBE Plume Diving

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Abstract

At a number of sites, a plume of methyl *tert*-butyl ether (MTBE) in ground water has dived below the screen of conventional monitoring wells and escaped detection. Techniques are needed to predict the vertical extent of MTBE in an aquifer. Two techniques that are emerging in the site characterization market are electrical conductivity logging and pneumatic slug testing performed in temporary push wells. These techniques were evaluated at a diving plume of MTBE in the aquifer that supplies water to the village of East Alton, Illinois. The plume stayed near the water table for the first 100 m from the potential sources and then dived below conventional monitoring over the next 100 m. At the location where the MTBE plume dived, the depth to water was 9.1 m below land surface. The first 10 m of material below the water table had an electrical conductivity near 100 mS/m, indicating silts and clays. An electrical conductivity near 25 mS/m, indicating sands or gravels, was encountered at a depth of 10.6 m below the water table, and the sands and gravel extended to a depth of at least 15.2 m below the water table. Pneumatic slug tests measured low hydraulic conductivity in the interval of silt and clay (0.34 and 0.012 m/d) and higher hydraulic conductivity in the interval with sands and gravels (12.5, 11.6, and 11.3 m/d). Ground water with the highest concentration of MTBE was produced just below the contact between the silt and clay and the sands and gravel.

Introduction

To control the costs of monitoring, most underground storage tank (UST) sites are characterized with conventional monitoring wells that are screened a few feet above and below the water table or by temporary push samples that are taken near the water table. Occasionally, this conventional monitoring approach fails to establish a connection between the potential sources of methyl *tert*-butyl ether (MTBE) contamination and impacted water supply wells. When contamination is missed because of the plume movement beneath the screens of the monitoring wells, the situation is commonly termed "plume diving." Weaver and Wilson 2000 discuss several environmental processes that may cause plume diving, illustrate the behavior with a case study on Long Island, New York, and offer recommendations to recognize and react to plume diving. The most widely recognized process that can produce plume diving is the burial of a plume by the recharge of clean water above it. The U.S. EPA provides a calculator on their web page that can be used to estimate plume diving caused by recharge (EPA On-line Tools for Site Assessment Calculation: Plume Diving; www.epa.gov/athens/learn2model/part-two/onsite/diving).

In 1999, the staff of the Illinois EPA investigated the source of MTBE contamination in municipal water supply wells in East Alton, Illinois. The plausible sources of MTBE were releases of gasoline at two service stations located 400 and 500 m northeast of the municipal water supply wells. In the first 250 m between the plausible sources and the wellfield, the land surface is paved or covered with buildings. In the first 100 m along the flowpath, the plume was easily delineated using shallow wells extending only a few meters into the water table. In the second 100 m along the flowpath, MTBE was not detected in shallow ground water but was detected in water from depths of 6.5 and 12.5 m below the water table. Because there was minimal opportunity for recharge through the paving, burial of the MTBE plume by recharge could not explain the absence of MTBE in the shallow wells.

The Illinois EPA recognized that the MTBE plume may have moved below a conventional monitoring network. To find the diving plume, they assumed that the MTBE plume would follow the flow of ground water and that ground water would flow through the more conductive material in the aquifer. They used electrical conductivity logging performed with push technology to characterize the hydrostratigraphy of the aquifer. This technique is affordable and produces data in real time. Southwest of the paved area, the water table was contained in a thick layer of silt and clay extending up to 7 m into the aquifer. Below

the silt and clay there was a layer of sand and gravel. They collected water samples from the layer of sand and gravel and successfully located the diving plume.

The National Risk Management Research Laboratory (U.S. EPA Office of Research and Development) was tasked by U.S. EPA Region 5 to conduct research to allow state regulatory agencies in EPA Region 5 to identify and predict diving plume behavior at ground water sites contaminated with MTBE. At many sites, plume diving will be controlled by recharge to the aquifer. At many other sites, plume diving will be controlled by the hydrostratigraphy of the aquifer. The approach to site characterization used by the Illinois EPA is appropriate for sites where plume diving is controlled by hydrostratigraphy. The U.S. EPA performed additional work at the site to confirm and extend the site conceptual model that was developed by the Illinois EPA and to evaluate their approach for site characterization to predict plume diving.

To better define the hydrostratigraphy of the aquifer, the electrical conductivity logging was repeated and extended as far into the aquifer as the tools would allow. The vertical distribution of hydraulic conductivity in the aquifer was defined with a downhole flowmeter survey in a well that was screened across most of the aquifer. The correspondence between hydrostratigraphy and hydraulic conductivity was evaluated by comparing the electrical conductivity log to the vertical distribution of hydraulic conductivity determined with the flowmeter test.

In recent years, pneumatic slug testing performed in temporary push wells has emerged as an affordable alternative to slug testing of permanent wells. To evaluate this approach, the estimates of hydraulic conductivity that were obtained from pneumatic slug tests were compared to the downhole flowmeter test.

The vertical distribution of the MTBE plume was defined at high resolution by sampling water every 3.3 m extending from the water table to the point of refusal of the push sampling tool. Inferences about the texture of aquifer material made from electrical conductivity logs were evaluated by acquiring core samples from a depth interval that had high concentrations of MTBE, high hydraulic conductivity, and low electrical conductivity, and a second interval of 3.3 m above the first that had low concentrations of MTBE, low hydraulic conductivity, and high electrical conductivity.

Finally, the geochemistry of the MTBE plume was characterized to evaluate the prospects for natural biodegradation of MTBE along the flowpath. If conditions for natural biological degradation of MTBE in the aquifer are unfavorable, MTBE contamination will persist along the flowpath from the potential source areas to the municipal wells.

History

The following description was extracted from case files that were provided by the Illinois EPA. The village of East Alton produces ~12 million L of ground water per day from a wellfield located in the American Bottoms, which is part of the floodplain of the Mississippi River. The wellfield is on the east side of the Wood River ~1800 m from the Mississippi River. In October 1999, MTBE was detected in water supply wells 6, 8, and 9 within the wellfield (Figure 1).

A major arterial highway (Illinois Route 3) extends across the catchments of the wellfield ~500 m from the impacted wells. The Illinois EPA identified two former gasoline service stations located immediately north and south of Illinois Route 3 as potential sources of the MTBE (Figure 1). At the potential source on the south side of Illinois Route 3, contamination with benzene, toluene, ethylbenzene, and xylenes (BTEX compounds) was discovered in backfill material around a UST in July 1994. The tanks were taken out of service and removed in October 1995. Because MTBE was detected in the drinking water supply wells, the monitoring wells surrounding the UST release were sampled for MTBE in January 2000. The maximum concentration of MTBE was 2200 µg/L. As part of an emergency response, the site of the former leaking UST was excavated to a depth of 10.7 to 12.2 m. Approximately 13,000 tons of contaminated materials were excavated in June 2000 and replaced with clean fill. The wells in the potential source north of Illinois Route 3 were also sampled in January 2000. The maximum concentration of MTBE in this round of sampling was 156 µg/L, the maximum concentration in subsequent rounds was 1800 µg/L. Approximately 16,000 tons of contaminated materials were removed and backfilled with clean fill. The areas that were excavated and backfilled are hatched in Figure 1.

The maximum concentrations of MTBE in East Alton water supply wells 6, 8, and 9 were 32, 61, and 560 µg/L, respectively. Figure 2 presents the concentration of MTBE in water supply well 9 over time. The concentration peaked in the summer of 2000. By the summer of 2001, the concentration was an order of magnitude lower.

Data were available from a short-term pumping test (300 min at 6240 L/min) conducted on well 1, one of the pumping wells in the wellfield. The transmissivity was estimated based on analysis of drawdown curves from two
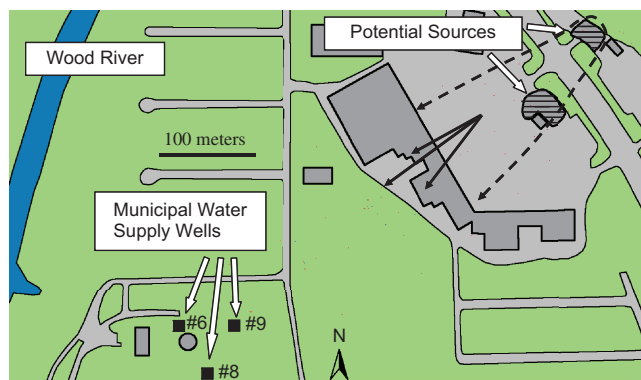

Figure 1. Relationship between the possible sources of MTBE and water supply wells contaminated with MTBE. The dotted line encloses permanent monitoring wells with detectable concentrations of MTBE. The three solid arrows indicate the direction of ground water flow in separate rounds of sampling in 2001, 2002, and 2003. The three solid arrows extend from the most contaminated permanent well at the site.
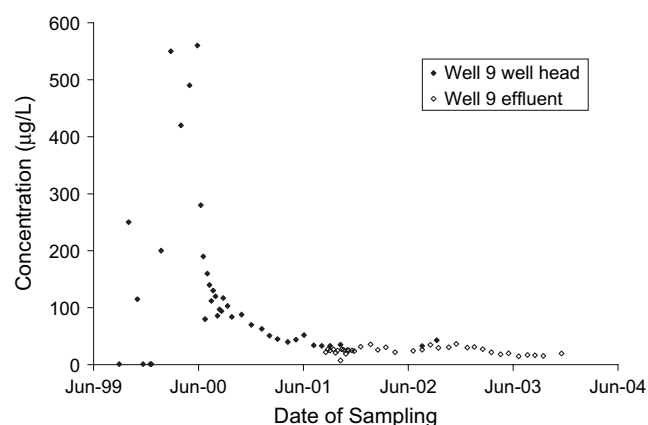
Figure 2. Concentration of MTBE in the most contaminated water supply well.

observation wells using the Theis type curve for a confined aquifer for the pumping data and the Theis recovery method for the recovery data. These estimates of transmissivity varied from 2320 to 2590 m^2/d. The transmissivity estimated from the specific capacity of the pumped well was 1510 m^2/d. The best estimate of the saturated thickness of the aquifer is 19.5 m. The corresponding estimate of the hydraulic conductivity ranges from 77 to 134 m/d.

In 1999, the Illinois EPA simulated the municipal wellfield using MODFLOW. Their model assumed an average rate of recharge of 20 cm/year, an average porosity of 0.30, and an average hydraulic conductivity of 66 m/d. The expected travel time of water from a point midway between the two possible source areas to water supply well 9 was 5 years. The concentration of MTBE reached a maximum concentration in the water supply wells in 2000. If the release of MTBE to the aquifer occurred in 1994, there is a good correspondence between the arrival time of MTBE in the monitoring record and the predictions of the model.

Ground Water Flow

The general direction of ground water flow is from the potential sources, then under a shopping mall, and then under a grassy undeveloped area to the municipal water supply wellfield. The area to the north and east of the wellfield is single-family residential housing (Figure 1). To estimate the direction of ground water flow from the possible source areas and the magnitude of the hydraulic

gradient, regression analysis was used to fit a plane to the elevation of the water table in permanent monitoring wells in the source areas. The regression was fit using the Optimal Well Locator application (Srinivasan et al. 2004). Results are presented in Table 1.

Over the three rounds of sampling, the direction of ground water flow varied by 23°. The hydraulic gradient varied by 45% over the three rounds of sampling. The fit to the regression was particularly good for data collected on August 9, 2001, and September 19, 2002. The fit was less good for data collected on January 8, 2003, but the regression was still usable.

On September 19, 2002, the depth to water was determined in most of the permanent wells at the site. Figure 3 compares the projected ground water contours from the regression to the actual water elevations on September 19, 2002. All the wells at the site fit the assumption that the water table was a plane.

Presumably, the MTBE that first reached the water supply wells would have moved through the most conductive material in the aquifer. As will be discussed later, the highest hydraulic conductivity determined at any depth interval in the aquifer was 51 m/d. The three solid arrows in Figure 1 represent the direction of ground water flow as estimated from the water elevation data collected in 2001, 2002, and 2003. The length of the arrows is the distance the ground water would have moved in 1 year under the prevailing hydraulic gradient if the effective porosity of the aquifer was 0.30 and the hydraulic conductivity was 51 m/d. If these assumptions of porosity and hydraulic conductivity are valid, the MTBE plume near the possible source areas is moving toward the municipal wellfield at a velocity on the order of 86 to 133 m/year.

Illinois EPA's Evidence for Plume Diving

The Illinois EPA mapped the distribution of MTBE in the aquifer by sampling permanent wells installed northeast of the shopping center and by using push technology to sample ground water southwest of the shopping center (Figure 4). The permanent wells were installed through asphalt paving. They are screened to a depth ranging from 9.1 to 10.7 m below land surface. The depth to water is ~8.5 m below land surface. Water samples from temporary push wells were acquired in the paved area southwest of the shopping mall. They were acquired at depths of ~9, 15, and 21 m below ground surface or 0.5, 6.5, and 12.5 m below the water table.

Table 1
Hydraulic Gradient and Direction of Ground Water Flow Near the Source Areas of the MTBE Plume

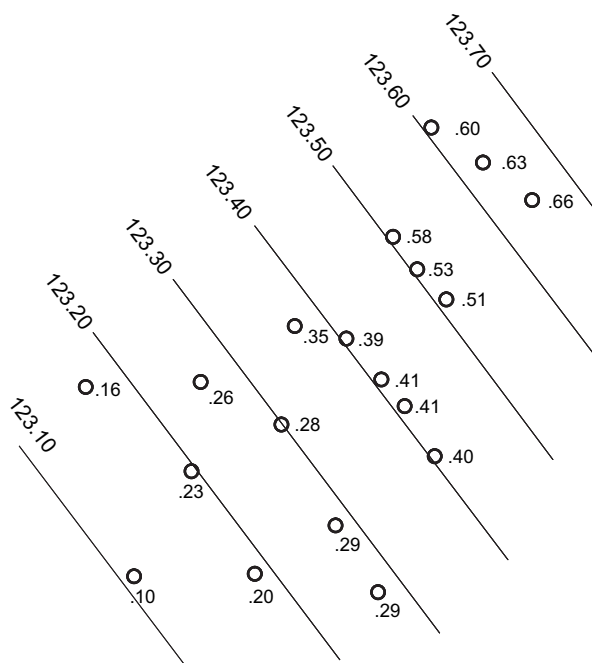| Date of Measurement	Number of Wells Measured	Hydraulic Gradient (m/m)	Direction of Flow (degrees clockwise from north)	Correlation Coefficient r^2
August 9, 2001	13	0.00138	240.5	0.97
September 19, 2002	19	0.00214	233.2	0.98
January 8, 2003	7	0.00159	217.9	0.77

Figure 3. Correspondence between measured elevation of the water table in permanent wells on September 19, 2002, and the contours produced by regression to fit a plane. Elevations are in meters. All the elevations fell between 123.0 and 123.7 m. To facilitate comparison, values are only provided for digits past the decimal point.

The permanent wells are coded in Figure 4 according to the maximum concentration of MTBE in any of four rounds of sampling extending from January 2000 to September 2002. The plume of MTBE was easily detected by the shallow monitoring wells in the parking lot northeast of the shopping mall. Although the screened intervals of the wells were very shallow, there is no indication of plume diving. The plume extended in the direction of ground
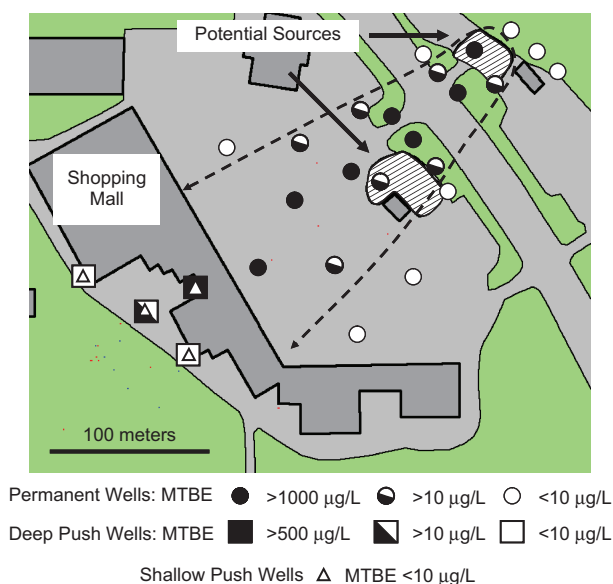
water flow that was predicted from water table elevations in the monitoring wells. The centerline of the plume contained wells with concentrations of MTBE >1000 µg/L.

In contrast to the behavior of the plume northeast of the shopping center, MTBE was not detected in shallow ground water southwest of the shopping center (Figure 4). Although MTBE was absent in the shallow ground water, it was detected at two push well locations at depths of 6.5 and 12.5 m below the water table. The area above the plume of MTBE was paved or roofed. There is little possibility that recharge could explain the diving plume. To better understand the influence of hydrostratigraphy on the behavior of the plume of MTBE, the Illinois EPA surveyed the aquifer using an electrical conductivity probe mounted on direct-push tools.

The electrical conductivity of sandy material that readily transmits ground water is lower than the conductivity of silts and clays. Their electrical conductivity survey revealed that the water table in the area southwest of the shopping center was contained within an interval dominated by silts and clays. The silt and clay interval extended ~18.3 m below land surface and 10.7 m below the water table. Apparently ground water moved beneath the layer of silt and clay as it flowed toward the municipal water supply wells. The plume of MTBE had "dived" below the elevation of the shallow ground water samples as it followed the flow of ground water in the aquifer.

Building on the work of the Illinois EPA, the National Risk Management Laboratory of U.S. EPA conducted a more detailed characterization of the flowpath between the possible sources of MTBE and the impacted water production wells. The characterization was performed at locations A, B, C, D, and E in Figure 5.

Materials and Methods

Electrical conductivity logs were acquired using a Direct Image Electrical Conductivity System with an SC400 Soil Conductivity Probe operated in the four-pole "Wenner" array (Geoprobe Inc., Salinas, Kansas). The

Figure 4. Distribution of MTBE in shallow ground water near the possible sources and in deeper ground water farther downgradient of the sources.
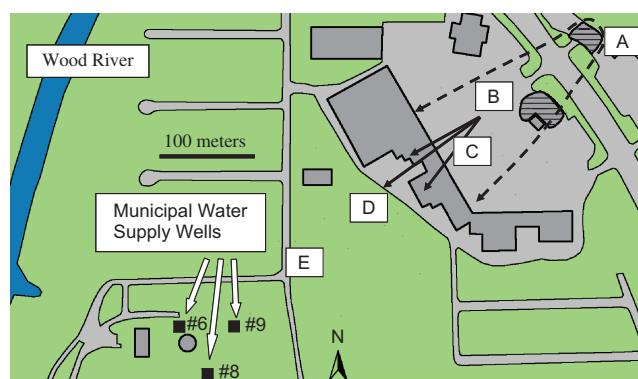

Figure 5. Locations used for detailed characterization of hydrostratigraphy using electrical conductivity, of the vertical extent of MTBE contamination, and of the vertical extent of hydraulic conductivity. The labels are centered on the sampling locations.

performance of this tool in a similar geological context is described by Butler et al. (1999) and Christy et al. (1994).

Water samples from permanent wells were acquired by suction lift using a peristaltic pump. Water samples from temporary push wells were acquired with a bladder pump. The inner diameter (I.D.) of the push rods was 5.4 cm; the length of the screened interval was 0.91 m.

Samples for analysis of volatile organic compounds were preserved with 1% trisodium phosphate. Concentrations of MTBE, *tert*-butyl ether (TBA), and BTEX compounds were prepared with a heated headspace sampler and determined by gas chromatography and mass spectrometry. Samples for methane were prepared by headspace sampling at ambient temperature and determined by gas chromatography with a thermal conductivity detector. Samples for sulfate and chloride were determined by capillary electrophoresis. Nitrate and nitrite were determined by Lachat flow injection analysis. Iron II was determined in the field with a CheMetrics test kit.

Pneumatic slug tests were conducted on discrete depth intervals by advancing temporary push wells into the aquifer. The screens of the push wells were 1.1 m long and 3.8 cm in diameter. The screen of the temporary push well was protected by a sheath while the push well was advanced into the aquifer. To perform the test, the sheath was pulled back to present the screen to the aquifer material. After the test was completed, the tools were retrieved, the sheath was installed over the screen, and the tools were driven to the next depth interval to be tested.

During the slug tests, the water level in the well was depressed using compressed air. Once the pressure in the well came to equilibrium with the applied air pressure, the air pressure was instantaneously released through an exhaust valve. A pressure transducer and data logger were used to monitor the water level over time as it returned to its original level. Multiple tests are conducted using different water displacements to ensure repeatable results. Data from the tests were analyzed using the methods of Butler and Garnett 2000. Pneumatic slug tests were performed on two permanent monitoring wells using the methods described by Butler 1998.

A sensitive electromagnetic borehole flowmeter was used to define the vertical distribution of hydraulic conductivity. The test was conducted in a well constructed at location D in Figure 5. At this location along the flowpath, the MTBE plume had moved ~10.7 m below the water table (19.8 m below land surface). The test well was 5.1 cm in diameter; it was installed through a hollow stem auger with a 15.2-cm I.D. and was screened from 11.6 to 25.3 m below land surface. The investigation consisted of measuring the vertical component of ground water flow at multiple intervals under undisturbed (ambient) conditions and during water injection at a constant rate of ~10 L/min. The rate of water flow from the well into an individual interval during steady-state injection or extraction is proportional to the hydraulic conductivity of the materials adjacent to the screen. Therefore, knowledge of the distribution of flow at each measurement interval along the screen allows interpretation of the hydraulic conductivity distribution relative to the average hydraulic conductivity of materials screened by the well (Young et al. 1998).

The electromagnetic borehole flowmeter used in this study was a commercially available system manufactured by Tisco Inc. (Roswell, GA), consisting of a 2.54-cm I.D. downhole probe and an electronics module. Probe design is based on Faraday's Law, which states that the voltage induced by an electrical conductor moving through a magnetic field is directly proportional to the velocity of the conductor. A voltage, proportional to the average water velocity, is generated as the conductor (i.e., ground water) flows through a magnetic field in the probe.

Measurements of vertical flow rates under ambient conditions and constant rate injection conditions were analyzed using methods described by Molz et al. 1994 and Young et al. 1998. The ambient flow rate at each measurement point was subtracted from the flow rate measured at that elevation during injection to obtain the portion of total flow due only to injection. The differences between these flow rates at different elevations represent the differences in horizontal flow into the formation due to differences in hydraulic conductivity of aquifer materials and hydraulic gradients. Assuming the hydraulic head distribution along the well screen was essentially uniform under the low injection rate conditions of these tests, the relative hydraulic conductivity distribution was then estimated using:

$$\frac{K_i}{K_{\mathrm{ave}}} = \frac{(\Delta Q_i - \Delta q_i)/\Delta z_i}{Q_p/b} \text{ for } i = 1, 2, 3 \ldots n$$

where, K_i is the relative horizontal hydraulic conductivity of interval i, K_{ave} is the average hydraulic conductivity of screened materials, ΔQ_i is the induced flow into interval i, Δq_i is the ambient flow to or from interval i, Δz_i is the thickness of interval i, Q_p is the total injection rate, and b is the aquifer thickness influenced by the test. A pneumatic slug test was used to determine the average hydraulic conductivity of the aquifer in the screened interval of the well used for the downhole flowmeter test.

Changes in Hydrostratigraphy along the Flowpath

The hydrostratigraphy was characterized along an inferred flowpath extending from the potential sources of MTBE contamination to the contaminated water supply wells. The sampling locations are depicted in Figure 5. Data from the electrical conductivity log are presented in Figure 6. In the experience of Butler et al. 1999 and Christy et al. 1994, an electrical conductivity of < 20 mS/m is indicative of sand and gravel, while an electrical conductivity >100 mS/m is indicative of clay and silt. At locations A, B, and C, the MTBE plume was readily detected by conventional monitoring wells with shallow well screens. As inferred from the low value for electrical conductivity, the water table at locations A, B, and C is contained within sandy material.

At locations D and E, the MTBE plume was not detected in the shallow ground water. At location D, the electrical conductivity log indicates a layer of clay and silt extending from the water table an additional 9 m into the aquifer. Similarly, at location E, the electrical conductivity log indicates a clay layer extending from the water table
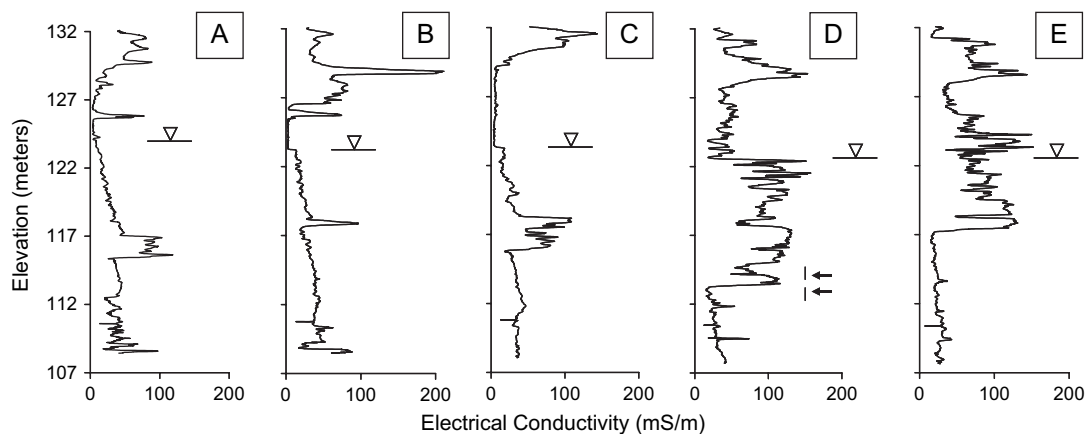
Figure 6. Distribution of electrical conductivity along the flowpath from the possible source areas of the MTBE plume to the water production wells.

an additional 5.2 ms into the aquifer. Notice at locations B, C, and D that there is a two- to threefold increase in the electrical conductivity at the water table. The marked increase in electrical conductivity at location D at an elevation of 122 m probably reflects the influence of the water table and does not indicate a change in the texture of the sediment.

To confirm the inferences made from the electrical conductivity logs, core samples were acquired from location D at elevations extending from 112.2 to 113.1 m (in a zone of low electrical conductivity) and from 113.7 to 114.6 m (in a zone of high electrical conductivity). The intervals are identified with arrows in panel D of Figure 6. The sediment recovered from the higher elevation with high electrical conductivity was plastic clay (see Figure 7). The sediment recovered from the lower elevation was coarse sand in a matrix of medium to fine sand (Figure 7).

Correspondence between Electrical and Hydraulic Conductivity

Location D was the first location along the flowpath between the potential sources and the impacted water supply wells where the MTBE plume had dived below the water table. The panel on the left side of Figure 8
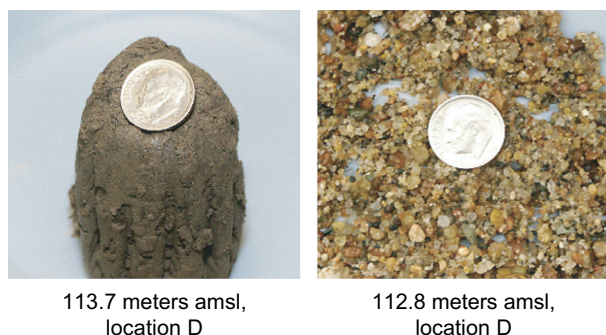

Figure 7. Texture of materials recovered in two core samples from Location D. Compare Figure 6 for the electrical conductivity of the depth interval sampled. Note that the sample from an absolute elevation of 113.7 m retained the imprint of the teeth of the core retainer.

compares the vertical distribution of electrical conductivity and hydraulic conductivity at Location D.

As determined from a pneumatic slug test, the average hydraulic conductivity in the well used for the flowmeter test was 14.3 m/d. In the first 9.1 m of the aquifer, the hydraulic conductivity as revealed by the downhole flowmeter test was low, 0.4 m/d or less. When the lithology transitioned from silt and clay to sand and gravel at an elevation of ~112.8 m above mean sea level (amsl) the hydraulic conductivity increased dramatically. The hydraulic conductivity at an elevation of 111.3 m was 51.2 m/d, compared to 0.27 m/d at an elevation of 114.3 m. As revealed by the downhole flowmeter test, 99% of the transmissivity in the interval between elevations of 120.4 and 106.7 m amsl was associated with the sandy material that extended between 114.0 and 106.7 m amsl.

The pneumatic slug tests conducted in the temporary push wells also revealed the low hydraulic conductivity of the shallow silts and clays and the sharp increase in hydraulic conductivity in the interval between 114.3 and 111.3 m amsl (panel on the right side of Figure 8). The hydraulic conductivity estimated from the pneumatic slug test at an elevation of 111.3 m was 12.5 m/d, compared to 0.33 m/d at an elevation of 114.3 m.

The hydraulic conductivity as estimated by the downhole flowmeter testing was approximately twice to three times the hydraulic conductivity estimated by pneumatic slug testing in temporary wells (Figure 8). Water was not added to the rods of the temporary push technology wells to equalize the pressure across the screens before the sheath was pulled away from the screen. As discussed by Butler et al. (2002), this can result in partial plugging of the screens. No attempt was made to develop the temporary push wells. Both of these practices may have contributed to the lower hydraulic conductivity determined in the temporary wells. In any case, the agreement between the estimate of hydraulic conductivity from the slug tests and the flowmeter tests were acceptable.

MTBE Plume Diving Predicted from Hydrostratigraphy

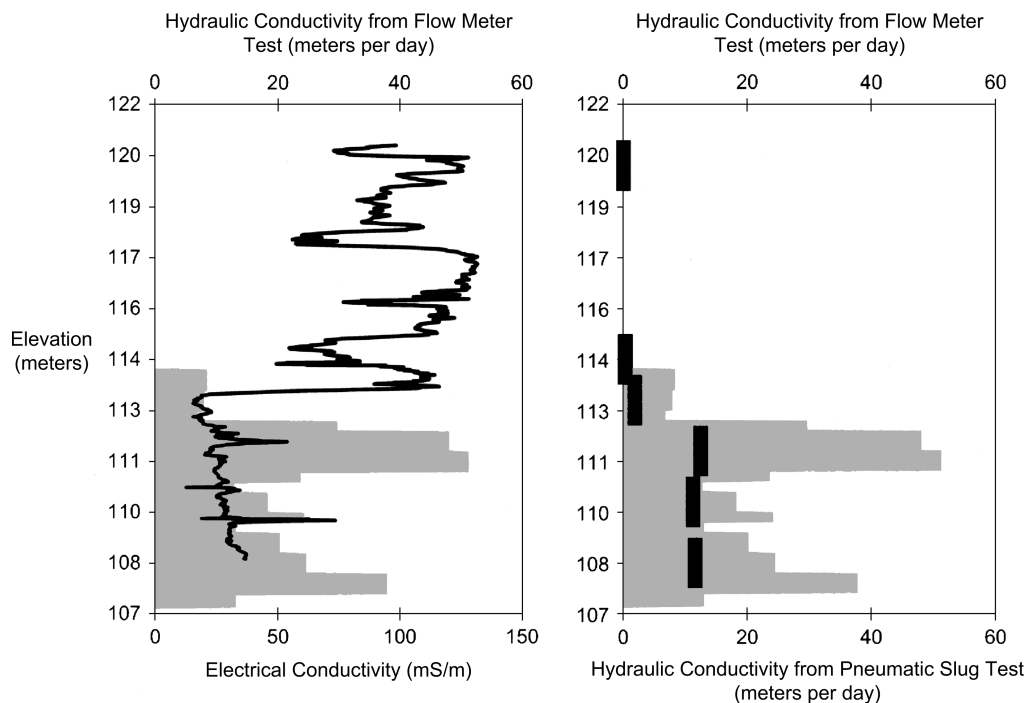Along the inferred flowpath between the potential sources and the impacted water supply wells, the highest

Figure 8. Inverse correspondence between electrical conductivity and hydraulic conductivity. The hydraulic conductivity distribution measured with a down-hole flowmeter test is depicted in the solid shape in both panels. The left panel compares the electrical conductivity to the hydraulic conductivity measured by a down-hole flowmeter test at location D in Figure 5. The right panel compares the hydraulic conductivity measured by a flowmeter test to the distribution of hydraulic conductivity measured by a pneumatic slug test. The vertical extent of the dark lines in the right panel represents the screened interval of the temporary push well subjected to a pneumatic slug test.

concentrations of MTBE were associated with sandy material with low electrical conductivity (Figure 9). Near the potential sources, the highest concentrations of MTBE were found near the water table (location B). In the location where the MTBE plume first dived below the water table, the highest concentrations of MTBE were found at the contact between the shallow clay unit and the underlying sand unit (location D). Further along the flowpath (location E), the highest concentration of MTBE was found more to the center of the sandy unit. Apparently, the plume of MTBE followed the hydrostratigraphic units with highest hydraulic conductivity.

Absence of Biodegradation of MTBE

There is a general perception that MTBE does not biologically degrade in ground water, even though MTBE has been shown to biologically degrade under aerobic and denitrifying conditions, iron-reducing conditions, sulfate-reducing conditions, and methanogenic conditions (Wilson 2003). The rates of degradation under aerobic and denitrifying conditions are fast (Borden et al. 1997; Salanitro et al. 2000; Bradley et al. 2001a). The rates of degradation under iron-reducing conditions may be fast when readily available iron is supplied to iron-reducing bacteria (Finneran and Lovley 2001), but the rate under iron-reducing conditions in an aquifer appears to be slow (Landmeyer et al. 1998). Laboratory studies show that MTBE may degrade under sulfate-reducing conditions (Somsamak et al. 2001; Bradley et al. 2001b), but the field studies available to date indicate that MTBE degrades slowly in aquifers under sulfate-reducing conditions (Wilson 2003).

At two field sites, the rate of MTBE degradation to TBA was rapid under methanogenic conditions (Wilson et al. 2000; Kolhatkar et al. 2002).

Many MTBE plumes are much longer than the associated plumes of BTEX probably because the BTEX compounds were biologically degraded but MTBE failed to degrade or degraded very slowly (Amerson and Johnson 2002; Landmeyer et al. 1998). This pattern is most likely when the MTBE is contained in ground water that is devoid of oxygen and nitrate, in water that has low concentrations of methane (<0.5 mg/L), and in water that has low concentrations of TBA compared to MTBE.

Table 2 compares the concentrations of MTBE, TBA, and BTEX compounds near the potential source of contamination, at the first location where plume diving was noticed, and further along the flowpath near the water supply wells. Although MTBE persists along the flowpath, the BTEX compounds are depleted. The ground water was essentially devoid of oxygen and nitrate, contained little methane, and the concentration of TBA was below the detection limit, which was much lower than the concentrations of MTBE. Based on the geochemical environment, MTBE should degrade slowly or not at all in the ground water at East Alton. Because it persists, there is an opportunity for the MTBE to move with the flow of ground water to the water supply wellfield.

Conclusions and Considerations

Two properties of the aquifer at East Alton are responsible for movement of the MTBE plume down below the
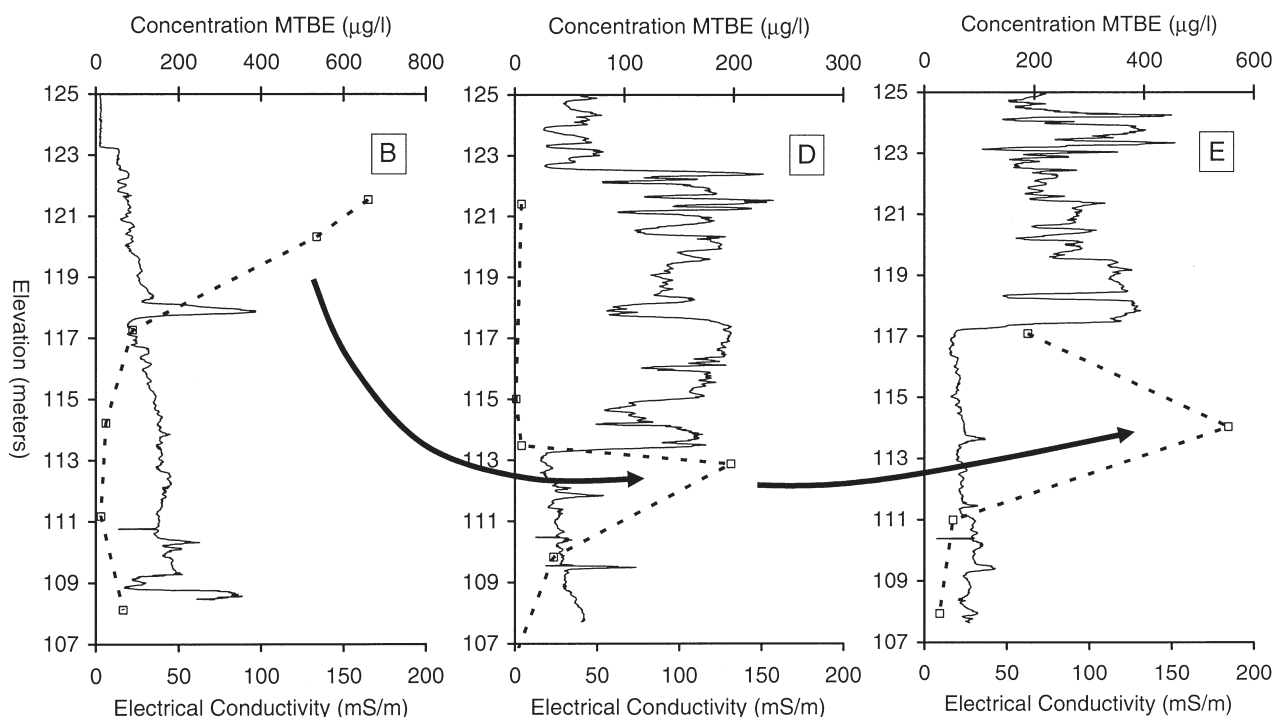
Figure 9. Association of higher concentrations of MTBE with sandy aquifer material (low electrical conductivity) along an inferred ground water flowpath from the potential sources of the MTBE (location B), to a location where the plume dived below the water table (location D), to the vicinity of a municipal wellfield (location E). Electrical conductivity logs are the solid lines; concentrations of MTBE are the dashed lines. See Figure 5 for a map of locations.

water table, which gave the appearance that the plume dived into the aquifer. First, the geochemistry of the ground water prevented rapid biodegradation of the MTBE and unacceptable concentrations of MTBE persisted along the flowpath. As a rule of thumb, long-term persistence of MTBE is possible in ground water that is depleted of oxygen and nitrate but is not accumulating significant concentrations of methane. Ground water that meets this geochemical profile is vulnerable to plume diving caused

Table 2
Concentration of Contaminants and Geochemical Parameters at the Most Contaminated Depth Interval at Three Locations along the Flowpath. Samples Collected in August 2001 and November 2001

Parameter	Location in Figure 5		
	B (near potential source)	D (downgradient)	E (farther downgradient)
MTBE (µg/L)	695	197	553
TBA (µg/L)	<10	<10	<10
Benzene (µg/L)	<0.5	<0.5	<0.5
BTEX (µg/L)	22	0.75	<0.5
Methane (mg/L)	0.06	0.17	0.31
Sulfate (mg/L)	232	46.2	46.5
Iron II (mg/L)	15	10	NA
Nitrate-N (mg/L)	<0.1	<0.1	NA
Oxygen (mg/L)	0.25	0.15	NA

by hydrostratigraphic influences, and characterization of the hydrostratigraphy and vertical distribution of hydraulic conductivity may be necessary to manage risk from MTBE contamination in these aquifers.

Second, the water table at the UST sites is in sandy material, but downgradient of the spill, the water table is in silts and clays. The natural flow of ground water in the aquifer found its way into a deep layer of sand and gravels lying below the layer of silts and clays at the water table. The hydrostratigraphy of the aquifer controlled the vertical distribution of MTBE contamination. The plume of MTBE simply followed the natural flow of ground water. This study validated the conceptual model of the diving MTBE plume that was developed by the Illinois EPA.

In this case, electrical conductivity logs proved to be an effective tool for recognizing the vertical distribution of hydrostratigraphic features that control the movement of water in the aquifer. However, the authors have conducted electrical conductivity logs at other sites where the logs failed to recognize the controlling hydrostratigraphic features. At these other sites, cone penetration testing revealed the hydrostratigraphic features that controlled the flow of ground water. In any case, it is worthwhile to recover and evaluate core samples to calibrate the log response at each site.

The downhole flowmeter test was conducted as a research activity to provide a benchmark for the electrical conductivity log and the pneumatic slug tests. Strictly speaking, flowmeter tests require a fully screened well across the aquifer of interest. However, such wells are expensive and are rarely available at UST release sites.

The pneumatic slug test offers a realistic alternative for mapping the vertical distribution of hydraulic conductivity, and identifying the optimum depth intervals for taking push samples or locating screens for permanent monitoring wells. Schulmeister et al. 2003, Butler 2002, and Butler et al. 2002 present a detailed description and evaluation of pneumatic slug testing at sites in Kansas that is very similar to the aquifer at East Alton, Illinois. Pneumatic slug testing is well developed and can be considered a routine tool for site characterization.

These site characterization tools are cost effective. During this investigation, a two-person crew set up the equipment for electrical conductivity logging, logged 80 feet of subsurface material, and then recovered and cleaned the tools in an average of 2 h. A two-person crew installed and recovered the push tools for the pneumatic slug tests, while a third person conducted the tests. One set of push tools was tested, while a second set was recovered, cleaned, and reinstalled at the next location. On average, the three-person crew conducted a pneumatic slug test every 2 h.

If time had been taken to develop the temporary push wells before they were slug tested, the three-person crew would have conducted a pneumatic slug test every 3 to 4 h. However, at this site, it was not necessary to develop the temporary push wells to discern the sharp contrast in hydraulic conductivity between the silts and clays at the water table and the sands and gravels that carried the plume of MTBE.

Acknowledgments

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